Abstract: The coherence between two CW laser diodes, each phase-locked to a femtosecond laser, is demonstrated. This method may be employed as a novel technique for generating high power, frequency stabilized and broadly tunable terahertz radiation.

In recent years, the development in the technology of ultrafast lasers and the stabilization of these ultrafast lasers has lead to significant advances in the tools for spectroscopy, coherent control and optical frequency synthesizers. The pulses emitted from femtosecond Titanium:Sapphire (Ti:S) lasers are constituted of an array of discretely spaced optical frequencies. Indeed, we now have the ability to stabilize the two degrees of freedom of an femtosecond laser which results in a fixed, discretely spaced optical ‘ruler’ to which other lasers may be compared and stabilized [1]. Here, we present the phase stabilization of two semiconductor CW laser diodes to the comb of a femtosecond laser and demonstrate coherence in the optical beat between the two laser diodes. Additionally, we heterodyne the outputs from these two CW laser diodes on a photoconductive switch and demonstrate emission of CW radiation at their difference frequency. The difference frequency between the laser diodes can be readily extended into the terahertz regime and hence, from optical rectification of the photoconductive switch, we can obtain narrow linewidth CW terahertz radiation with excellent frequency and amplitude stability.

Figure 1: (a) Configuration for the stabilization of two CW laser diodes to the comb of a femtosecond laser. LD1: laser diode 1, λ/2 W: half waveplate, P: polarizer, BS1: 50/50 beam splitter 1, G: grating 1, PD1: photodiode 1. The polarizers in the laser diode beam paths reduce the noise caused by the unpolarized spontaneous emission (b) Representation of the spectral output of two laser diodes and the comb of a femtosecond laser.

To stabilize the two CW laser diodes separately to the comb of the femtosecond laser, we employ the configuration shown in Fig. 1(a). The first beam splitter (BS1) combines the laser diodes and the second beam splitter (BS2) combines the femtosecond comb with the laser diodes. Each CW laser diode is centered at 850 nm with optical powers of 100 mW (DL1) and 40 mW (DL2). The 92.8 MHz femtosecond laser is centered at 790 nm with a FWHM bandwidth of approximately 65 nm and output power of 340 mW. To obtain an interference signal between each CW laser diode and the femtosecond laser, a diffraction grating (G1, G2) is used to spectrally disperse the femtosecond beam. The signal from the photodiode, with only the femtosecond laser as input, consists of a sequence of RF peaks spaced by the repetition rate \( f_{\text{rep}} \) of the laser. The signal from the photodiode, with both the laser diode and femtosecond laser as simultaneous inputs, consists of the femtosecond \( f_{\text{rep}} \) peaks as well as a sequence of RF beat notes arising from the optical
interference of each optical femtosecond comb line with the CW laser diode [2].

We isolate one RF beat note from the array and lock this RF signal to a synthesizer using a phase-locked loop (PPL), as shown in Fig. 2. The digital phase detector is employed to increase the dynamic range of the PPL, as there is appreciable noise on the laser diode frequency in the kHz-MHz regime. We feed the error signal back to the laser diode current to control its frequency.

![Block diagram](image_url)

**Figure 2:** Block diagram for the phase-locked loop that stabilizes each CW laser diode to the comb of a femtosecond laser. The synthesizer provides a reference to electronically mix the 70 MHz RF beat between each laser diode and the femtosecond comb, producing an error signal that is sent into the loop filter for processing. This signal is then feedback to the current controller of the laser diode.

When the laser diodes are close enough in frequency so that they cannot be spatially resolved by the gratings, RF beats resulting from the optical interference from each laser diode and the femtosecond laser may be observed at the photodiodes. Since the presence of simultaneous laser diode beats prevent locking of either laser diode, we eliminate the simultaneous beats by cross polarizing the laser diodes. A waveplate in the femtosecond beam ensures the interference signal of each laser diode with the comb (Fig. 1). To characterize the relative beat between the two locked CW lasers, we observe the optical beams reflected from BS 1 in Fig. 1(a). When the two laser diodes are close in frequency, we are able to detect their optical beat with one another using a fast photodiode.

![Graphs](image_url)

**Figure 3:** (a) Beat between each laser diode and the femtosecond Ti:S comb when the optical separation between the diodes is 25.5 GHz. The S/N of each of these locked beats is ~36 dB in a 100 kHz bandwidth. (b) Beat between the two laser diodes when each is individually locked to the femtosecond comb when they are optically separately by 2.1 GHz and 25.5 GHz. (c) Beat between a harmonic mixer and the signal from the photoconductive switch when the two laser diodes are separated by 39.755 GHz.

The linewidth of the difference frequency between the two laser diodes is related to the linewidth of each individual laser diode. The phase-locked loop (PPL), tightly controls the frequency excursion of the laser
diodes. Figure 3(a) shows the in-loop linewidth of each laser diode locked to the comb. The temporal coherence between the laser diode and the femtosecond comb, due to the PPL, is demonstrated by the central peak in the linewidth. This spike has a very narrow frequency of much less than a 100 Hz. Since each individual laser diode is temporally coherent with the femtosecond laser, there is then a coherence established between the two laser diodes. Figure 3(b) shows the coherence between the two laser diodes when their optical frequencies are separately by 2.1 GHz and 25.5 GHz.

By heterodyning the outputs from the two CW lasers on a photoconductive spiral antenna on the substrate LT-GaAs, we are able to generate CW radiation over a broad range. As shown in Fig.1(a), we use an objective to focus the spatially overlap CW beams onto a gold spiral antenna. A waveguide harmonic mixer generating 40 GHz is placed after the Si lens to detect the CW signal generated by the antenna. Figure 3(c) presents the beat between the radiation from the photoconductive switch, captured from free space onto this waveguide and the harmonic mixer’s 40 GHz signal when the two laser diodes are separated by 39.755 GHz. In this demonstration, the laser diodes were not stabilized to the femtosecond comb.

By tuning the CW lasers a terahertz apart we can generate phase CW stable terahertz radiation from the photoconductive switch. This radiation is expected to have a narrow linewidth as it corresponds to the optical linewidth of the constituent CW laser diodes, which are controlled by the PPL. Indeed, by locking the repetition rate of the femtosecond laser to an optical standard, we can conduct studies of absolute frequency measurements of molecular lines in the THz domain. Furthermore, since each laser diode may be tuned by several nanometers, the distinct advantage of the femtosecond laser is that it allows for the difference frequency between the two laser diodes to extend from near DC to THz frequencies.

Hence, we have demonstrated an all solid-state system that has generated a temporally coherent CW difference frequency of 2.1 GHz to 25.5 GHz between two laser diodes individually locked to the comb of a femtosecond laser. We have also demonstrated that we can generate CW radiation from the photoconductive switch when the two laser diodes are optically separated by 39.775 GHz. We have locked the two laser diodes approximately 1 THz apart and are in the process of establishing the setup necessary for the generation of CW terahertz radiation from a photoconductive switch and detection with a bolometer. In conclusion, this method has the potential for high resolution spectroscopy in the infrared THz region with tunable CW radiation that possesses high spectral power and excellent frequency and amplitude stability.